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Effects of fuels, weather, and management on fire severity in a southeastern pine savanna

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EFFECTS OF FUELS, WEATHER, AND MANAGEMENT ON FIRE SEVERITY IN A SOUTHEASTERN PINE SAVANNA

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ABSTRACT

Small scale heterogeneity in fire severity is important in pine flatwood communities of southeastern United States. Heterogeneity in fire severity, in turn, is important because if produces heterogeneity of vegetation in these habitats. By measuring fuel scorch and consumption immediately after a fire, I documented small-scale heterogeneity of fire severity. I found that pre-fire fuels and management had significant effects on fire severity, whereas weather did not. Weather, however, demonstrated variation over the 2007 fire season and is clearly a primary driver of fire behavior and effects in natural fire regimes (Johnson 1992). I attribute the lack of weather influence on fire severity to mainly to management practices within the Avon Park Air Force Range. The prescribed fire regime at the APAFR consists of two conflicting goals: 1) ecosystem integrity and 2) control. Fire managers burn particular areas under particular weather conditions to reduce the potential for spotting or jump fires. Additionally, outside agencies with other objectives often dictate when prescribed fires can occur. In particular, state forestry agencies often impose burn bans precisely when natural, lightning initiated fires historically occurred and produced ecologically sound effects. My study suggests that the range of fire severity seen in a natural fire regime is greatly reduced in a prescribed one. This effect may reduce species diversity by reducing opportunities for recruitment, removal of competitive dominants, and encroachment by plants that are not fire tolerable.

INTRODUCTION

Variation in fuels and weather is an important determinant of fire behavior, and thus fire effects, in a natural fire regime. Pine savannas of the southeastern United States have evolved with high frequency, lightning initiated fires for millions of years, in which their effects select for pines and control growth of the midstory. Pyrogenic properties of the endemic flora of pine savannas promote fires, including volatile compounds found in shrubs, palmettos, and pine needles that accentuate fuel continuity and increase the intensity of the fires (Ryan 2002, Sah et al. 2006; Hiers et al. 2009). Natural, lightning fires produce heterogeneity in small-scale fire severity, as indicated by burned vegetation, reducing competitive dominants and creating openings that allow regeneration and colonization of plant species (Hiers et al. 2009; Sah et al. 2006; Thaxton and Platt 2006). This variation, in turn, promotes high biodiversity and contributes to the overall species demography that is characteristic of these landscapes (Waldrop et al. 1992; Rice 1993; Williams et al. 1994; Platt 1999; Outcalt 2000; Collins and Smith 2006; Sah et al. 2006; Thaxton and Platt 2006).

Fuel conditions of southeastern pine savannas that affect fire severity are strongly influenced by weather conditions in a natural fire regime. Small-scale weather conditions such as relative humidity, ambient temperature, and wind speed influence the moisture content of fuels throughout the day and thus fire behavior. Larger scale weather, such as drought, allows desiccation of wetter landscapes (e.g., bogs, depression slopes, sloughs, swamps), increasing continuity of litter fuels in pine savannas (Slocum et al. 2003; Gill and Allen 2008). Similarly, in some habitats, above average rainfall promotes increased growth of herbaceous plants, which become cured during subsequent drought conditions, increasing fuel continuity and promoting fire spread (Gill and Allen 2008). Thus, interactions between fuels and weather influence fire behavior, and thus fire effects in southeastern pine savannas.

Management utilizes the interactions among fuels and weather to prescribe fires while working towards two important, yet conflicting, goals. First, prescription fires reduce fuels and decrease the potential for catastrophic fires, protecting infrastructure. Outside forces, however, can prevent prescription fires during times of drought (e.g., burn bans issued by state forestry agencies), thus controlling when and where prescribed fires occur. The second goal of a prescribed fire regime is to produce a fire regime that maintains species diversity, ecosystem function, and ecosystem integrity. Southeastern pine savannas harbor species that evolved with and thereby became dependent on frequent, lightning-initiated surface fires. These fires, however, were of greater abundance and burned large areas during drought conditions (Platt 1999; Beckage et al. 2005; Slocum et al. 2007), precisely when burn bans are implemented. Thus, there is conflict between the control and environmental goals of management concerning the timing and location of fires, potentially resulting in reduced small-scale heterogeneity that is seen in a natural fire regime. This small-scale heterogeneity in fire effects is important because it is thought that the most ecologically relevant fire effects occur at this level (Mitchell et al. 2006; Thaxton and Platt 2006; Hiers et al 2009).

One way to measure small-scale heterogeneity of fire effects is to determine the fire severity, as indicated by plant scorch and consumption, of fuel components immediately after the burn. This measure of fire severity, however, is often not documented in scientific studies. Most studies document fire severity as the percent consumption between pre- and post-fire fuel weights (Cheney et al. 1993; Sah et al. 2006; Thaxton and Platt 2006) and recovery or mortality of vegetation in the ensuing growing season (Williamson and Black 1981; Thaxton and Platt 2006). Other studies examine how pre-fire fuel characteristics affect fire behavior without documenting post-fire fuel characteristics (Bessie and Johnson 1995; Baeza et al. 2002; Hiers et al. 2009). Fuel consumption immediately after the fire, however, can influence second-order fire effects such as mortality of shrubs, colonization, recovery, and species demography (Hiers et al. 2009). Thus, the examination of small-scale fire severity, with regards to fuel scorch and consumption, immediately after a fire provides a link between the fire's behavior and delayed fire effects.

In this study, I asked the question: how do weather, fuels, and management affect fire severity (as indicated by fuel scorch and consumption) in a prescribed fire regime. I first satisfied three objectives to answer this question: (1) measure variability of weather during fires in the 2007 fire season; (2) determine correlations of these weather variables; and (3) determine correlations of different fuel quantities. My study site consisted of pine flatwood communities at Avon Park Air Force Range (APAFR; south central Florida, USA). Fire managers at the range prescribe fires during different times of the year (generally from January to August), potentially producing a wide range of fire effects, including severity of fuel components. I examined fuel quantities prior to each fire, measured weather during the fires, and assessed fire severity of fuels immediately after each fire. Independent variables, including weather during the fires and pre-fire fuel quantities, were analyzed separately using a principal components analysis to determine correlations and reduce the number of variables. I then ran stepwise multiple regressions with fuel and weather principal components, along with ignition technique, to determine significant effects on immediate fuel scorch and consumption. Fire managers and policy makers can use this information to develop prescribed burning plans that better promote ecosystem integrity and function.

METHODS

Study site

Avon Park Air Force Range (hereafter, APAFR) in south-central Florida, USA (Polk and Highland Counties; 27º35’ N, 81º16’ W) covers 43,000 hectares, of which 900 ha are used for military bombing ranges. Approximately 33,000 ha of the range are in natural vegetation, including landscapes such as upland scrub and pine savanna communities, which transition down-slope into prairies and ultimately wetlands. My study focused on the pine flatwood communities, which included wet and mesic flatwoods. In general, flatwoods are characterized as having few and scattered tree species, with a dense and diverse groundcover. Scattered longleaf pine (*Pinus palustris*) and slash pine (*Pinus elliotti*) are the most common tree species within pine flatwoods. In most areas, the groundcover is dominated by wiregrass (*Aristida behrichiana*), whereas areas with histories of infrequent fires may be dominated by dense patches of saw palmetto (*Serenoa repens*) or shrubs (e.g., *Ilex* and *Quercus* spp.). Another flatwood community within my study included cutthroat (*Panicum abscissum*) seeps; these are characterized as having nearly 100% cover of cutthroat grasses with fetterbush (*Lyonia lucida*) and other herbaceous species not commonly found in areas dominated by wiregrass (Orzell 1995).

The APAFR has a highly seasonal subtropical climate, with more severe dry periods than either northern or southern Florida (Chen & Gerber 1990). During the dry season (October to May), rainfall is typically from winter storm fronts (Chen & Gerber 1990) and averages 45 ± 15 cm (mean ± 1 SD) (Slocum et al. unpublished data). The wet season normally extends from late May to early October, with a mean rainfall more than double that of the dry season (89 ± 27 cm). During most afternoons of the wet season, the sea breeze, daily convective rains, and thunderstorms influence precipitation (Chen & Gerber 1990). Thus, weather within my study site varies both seasonally and daily, potentially influencing fire behavior, and thus, fire severity.

Fire regimes of the Avon Park Air Force Range

Prescribed fires are the primary management tool for influencing ecosystem function and integrity at the APAFR. In 1990, the prescribed fire regime was reevaluated and made to incorporate more growing season fires on an increased frequency of every two-to three years for pine flatwood communities (The Nature Conservancy 1994; Van Hook 1995). Prescribed fires currently account for nearly 90% of total area burned (data from 1996-2004; Slocum et al. unpublished data) and managers use composites of ignition techniques, including head, backing, and flanking fires, to control fire behavior (Van Hook 1995). Fire managers prescribe fires to satisfy two main objectives: 1) for containment, and 2) to maintain habitats. Ordnance fires, or fires ignited by practice bombs, must be contained in the site. Thus, fire managers burn the entire installation to reduce fuels and the potential for catastrophic fires. Outside objectives, including burn bans issued by the state forestry, protection of endangered species by the Endangered Species Act, and consideration of other land users (e.g., foresters, ranchers, campers, and hunters), must also be incorporated in the prescribed fire regime. Management goals, along with the many outside objectives, however, often have conflicting strategies, forcing managers to compromise and resulting in fires that may not produce the most beneficial effects.

Experimental design

In the 2007 fire season (January to July), fire managers at the APAFR prescribed fires within pine flatwood communities. During this time, I gathered data from 115 plots within 44 different fires. Each fire was contained within a burn unit, which is compartmentalized by firebreaks, such as roads, ditches, disc lines, or other landscape types (e.g. pine plantations and hardwood hammocks). Before a fire was scheduled, I randomly placed 2-5 circular fuel measurement plots (12 m diameter) within each burn unit. For each plot I obtained the latitude and longitude coordinates using a GPS device.

To determine how fuel quantities affected fire severity, I assessed the pre-fire fuel composition and structure of four dominant fuel components: dead fine fuels (browned grass, leaf litter, and pine needles), live fine fuels (grasses and forbs), live shrubs, and live palmettos. The structure of each fuel component was characterized as the average height of each component and the percentage of the plot surface containing the component. I then used the height and width of each fuel component within a plot to estimate fuel quantities (using the equation for volume of a cylinder). In addition, composition and structure of pine trees were assessed as the number of pines in each plot and their diameter at 1.4 m (DBH). A total basal area within each plot was then calculated.

During the fires, assessments of weather and management were taken. To measure the potential effects of weather conditions on fire severity, I determined relative humidity (RH), wind speed, and atmospheric temperature using a Kestrel hand-held weather meter during each fire. Weather data was collected as the fire spread through each plot, providing me with local weather conditions. The Keetch-Byram Drought Index (KBDI) was obtained from a weather station (S65CW) located 20 km southeast of the APAFR. These data were obtained from the DBHYDRO browser of the South Florida Water Management District (http://www.sfwmf.gov). Soil moisture, serving as my second drought index, was obtained from a nearby weather station. The seasonal timing of the fires in my study was determined as the days before or after the onset of the wet season (hereby referred to as Onset). The date of Onset was designated as the minimum cumulative rainfall anomaly, which was found to be May 29, 2007 (Camberlin and Diop 2003; Slocum et al. unpublished data). To measure management practices on fire severity, ignition techniques (i.e., backing, flanking and head) were also documented for each plot by visual observation of flam direction relative to wind direction.

Immediately after a plot burned, I scored the scorch and consumption of the burned fuel components (unburned vegetation omitted). Scorch indicated browned vegetation, whereas consumption indicated where the vegetation was consumed in the fire. This assessment was made within two weeks after each fire. Vegetation growth that may have occurred during these weeks following the fire did not obscure the assessment of fire severity because the scorched or consumed areas were distinguishable from the new growth. Severity scores (adopted from Slocum et al. 2003) of the fuels components were assessed as below:

- Dead fine fuel. 1: top layer scorched or partially consumed, but bottom layer not scorched. 2: both layers fully scorched or partially consumed, but not completely consumed. 3: both layers fully consumed, leaving bare soil or ash only.
- Live fine fuel. 1. partial scorch or consumption, some stalks unconsumed. 2: stalks fully consumed to base. 3: stalks fully consumed, including base.
- Palmettos. 1. fronds partially scorched. 2. fronds fully scorched or partially consumed. 3. fronds fully consumed, petioles scorched. 4. petioles consumed. 5. base consumed, partially or completely.
- Shrubs. 1. leaves partially scorched. 2. leaves completely scorched. 3. leaves consumed. 4. secondary branches consumed. 5. primary branches or stems consumed.

In most plots, the scores of fire severity of any given fuel component was patchily distributed due to both temporal and spatial variation in the fuels. For example, palmettos in a plot were often consumed at scores two and three, but at different percentages for each score. I therefore adjusted for separate patches of fuel components that burned at different severities within a plot using the formula below:

$$S_{ij} = \sum_{k=1}^{x}(S_{ijk} * P_{ijk}) \qquad \text{Formula 1.0}$$

where S_{ij}=overall severity score of fuel component, j, in plot, i; S_{ijk}= severity score of the fuel component, j, within patch, k, in plot, i; P_{ijk}=the proportion of the severity score within the patch, k.

I standardized the overall severity rankings of each fuel component by dividing the severity ranking of the fuel from Formula 1.0 by the maximum severity of that fuel component within the study:

$$SI_{ij} = \frac{S_{ij}}{S_{jmax}} \qquad \text{Formula 1.1}$$

where SI_{ij}= overall fire severity of fuel component, j, in plot, i; S_{ij}= severity score of fuel component, j, in plot, i; and S_{jmax}= maximum fire severity of fuel component, j.

To measure how severely the fires affected the pine trees (i.e. the canopy), I documented the height at which trunks were scorched (char height) and estimated the percent of needles that were scorched or consumed in the canopy. I averaged the char height, needle scorch, and needle consumption of the pines within each plot to obtain a single value for each of the three variables.

Data analysis

To describe seasonality over the 2007 fire season, I plotted weather variables during fires against seasonal timing. Seasonal timing was represented as the days before or after the Onset. Onset was valued with a zero and seasonal timing of a given fire within a plot is represented with negative values for those that occurred before Onset and positive values to plots that were burned after Onset.

To avoid problems involving the high number of independent variables in this study, and the high multicollinearity that exists among them, I ran a principal component analyses (PCA). This was done separately for pre-fire fuel quantities and fire weather using PROC FACTOR, variation rotation=VARIMAX (of SAS release 9.1.3, SAS Institute, Cary, NC). To examine relationships among fuel components, the PCA grouped variables based on their Pearson Correlations into separate principal components (PCs). PCA included dead fine fuel, live fine fuel, shrubs, palmettos, basal area of pines, and the time since last fire (a surrogate for fuel build-up). The PCA of weather variables included ambient temperature, KBDI, RH, soil moisture, wind speed, and seasonal timing (days before or after Onset). Correlations of the individual variables were examined and the highest within each PC were used to "define" it. PCs with eigenvalues greater than one were retained for future analyses.

A severity index was estimated for three vegetation layers: 1) groundcover fuels, 2) midstory fuels, and 3) the canopy. The groundcover layer included severity scores for dead and live fine fuels, while the midstory layer included severity scores for shrubs and palmettos. Within a plot, the two fuel components within each layer burned similarly and were therefore correlated, as determined using PROC CORR (of SAS release 9.1.3). Thus, by separating the fuels into layers, the number and multicollinearity of the dependent fuels was reduced.

To determine the fire severity of the midstory and groundcover layers, I developed Formula 2.0. I multiplied the standardized severity rankings of included fuel components by the pre-fire volume of that fuel component. To standardize the volume, I first divided by the total pre-fire fuel volumes of fuel components that make up the layer. I then averaged these severity indices:

$$SI_l = \sum_{j=1}^{x}(SI_{ij} * \frac{V_{ij}}{V_{jltotal}}) \div N_{ijl} \qquad \text{Formula 2.0}$$

where SI_l=fire severity of the fuel layer, l; SI_{ij}=adjusted severity of the fuel component, j, in plot, i; V_{ij}=pre-fire volume of fuel component, j, within plot, i; $V_{jltotal}$=total pre-fire fuel volume of fuel components, j, within fuel layer, l; and N_{ijl}= total number of fuel components, j, of layer, l, that exist within plot, i.

The variables representative of the severity of the canopy (char height in feet, needle scorch and consumption in percent), however, possessed different units and therefore could not be adjusted and standardized as the severity indices of the groundcover and midstory were. Thus, I ran another PCA on these three variables to obtain a single severity index for fire severity of the canopy (pines).

To determine how fuel, weather, and ignition technique affected fire severity, I ran separate multiple regressions for the overall severity of each layer (i.e. groundcover, midstory, and canopy). PCs retained from the pre-fire fuel and fire weather PCAs, along with ignition type (e.g. head, backing, or flanking), were used as the independent variables in each model (fuel: PC1, PC2, PC3 and weather: PC1 and PC2). I chose a conservative selection criterion, with a p-value for entry at 0.15 and a p-value to stay at 0.05. The GLMSELECT procedure (of SAS release 9.1.3) was used because it allows for 2-way interactions among the variables as well as allows for the class variable, ignition technique.

To verify that the selection criterion was conservative enough, I ran the selected variables form the multiple regressions a second time and observed the Schwarz Bayesian criterion (SBC). This model indicated similar results; therefore I chose to report the models based on the p-values. I also adjusted for potential random effects of time and space by running chosen variables within each models using the MIXED procedure with date of fire and burn unit included as random effects.

RESULTS

2007 fire season

The 2007 fire season during my study at the Avon Park Air Force Range lasted from February 8 to July 3. Within this time, I gathered data from 44 fires within burn units (areas compartmentalized by firebreaks). In general, multiple units were burned during a single burn day, with fire ignition times ranging from the early morning to the early evening. Composites of techniques (e.g., ignition techniques, firebreaks, spot ignitions) used by the fire manager at the APAFR varied based on the resources available (e.g., personnel, fire trucks, equipment). Initially, backing fires were typically set along the firebreaks, until an area of blackened vegetation was established. Afterwards, a combination of head, backing, and flanking fires were set throughout the burn unit as wildland firefighters worked the edges of the unit, controlling for spotting or jump fires.

During the 2007 fire season, weather was measured as the fire spread through each plot. A total of 115 plots were assessed, spanning the entire fire season. A gap, however, exists from April 15 through June 2 due to dry conditions when managers did not conduct prescription fires at the APAFR in accordance to a burn ban. This gap includes the transition from the dry season to the wet season, during which fires typically burn at a greater severity due to dry conditions (Beckage et al. 2003, 2005; Slocum et al. 2003, unpublished data). This gap also included the onset of the wet season (Onset), May 29, 2007, which is the date of the minimum cumulative rainfall anomaly (Chamberlain & Diop 1990; Slocum et al. unpublished data). By plotting weather during the fires against days before or after Onset, the seasonal timing of fires can be determined.

Seasonality of fire weather

Fire weather during the 2007 fire season showed considerable seasonal variation. To examine the variation of weather conditions during fires at the APAFR in my study, I plotted weather conditions against the difference in days from the Onset (Figure 1). As the fire season progressed, both relative humidity and ambient temperature showed general increasing trends (Figure 1A, 1B). Additionally, values for relative humidity and temperature were more variable during fires prior to Onset, whereas only larger values occurred during fires after Onset. The Keetch-Byram Drought Index (KBDI), on the other hand, generally decreased as the fire season progressed (Figure 1C). Soil moisture (at 30-60 cm depth) and wind speed during fires demonstrated non-linear relationships with seasonality. As the Onset was approached, soil moisture slowly decreased, reached its lowest values near Onset, and quickly increased after Onset (Figure 1D). Wind speed was variable throughout the season, but tended to be higher during fires closer to Onset than during fires earlier in the dry season or later in the wet season (Figure 1E). Thus, the seasonal variation in weather conditions was determined during fires in the 2007 fire season.

Relationships among weather variables

A principal component analysis (PCA) of weather variables (i.e. relative humidity, wind speed, temperature, KBDI, soil moisture and seasonal timing) during fires separated weather into two principal components (PCs) (Table 1A). Together, these PCs explained 71% of the total variation in the data set. The first component (PC1) explained 45% of the total variance and included seasonal timing (days before or after Onset), ambient temperature, and KBDI. I named

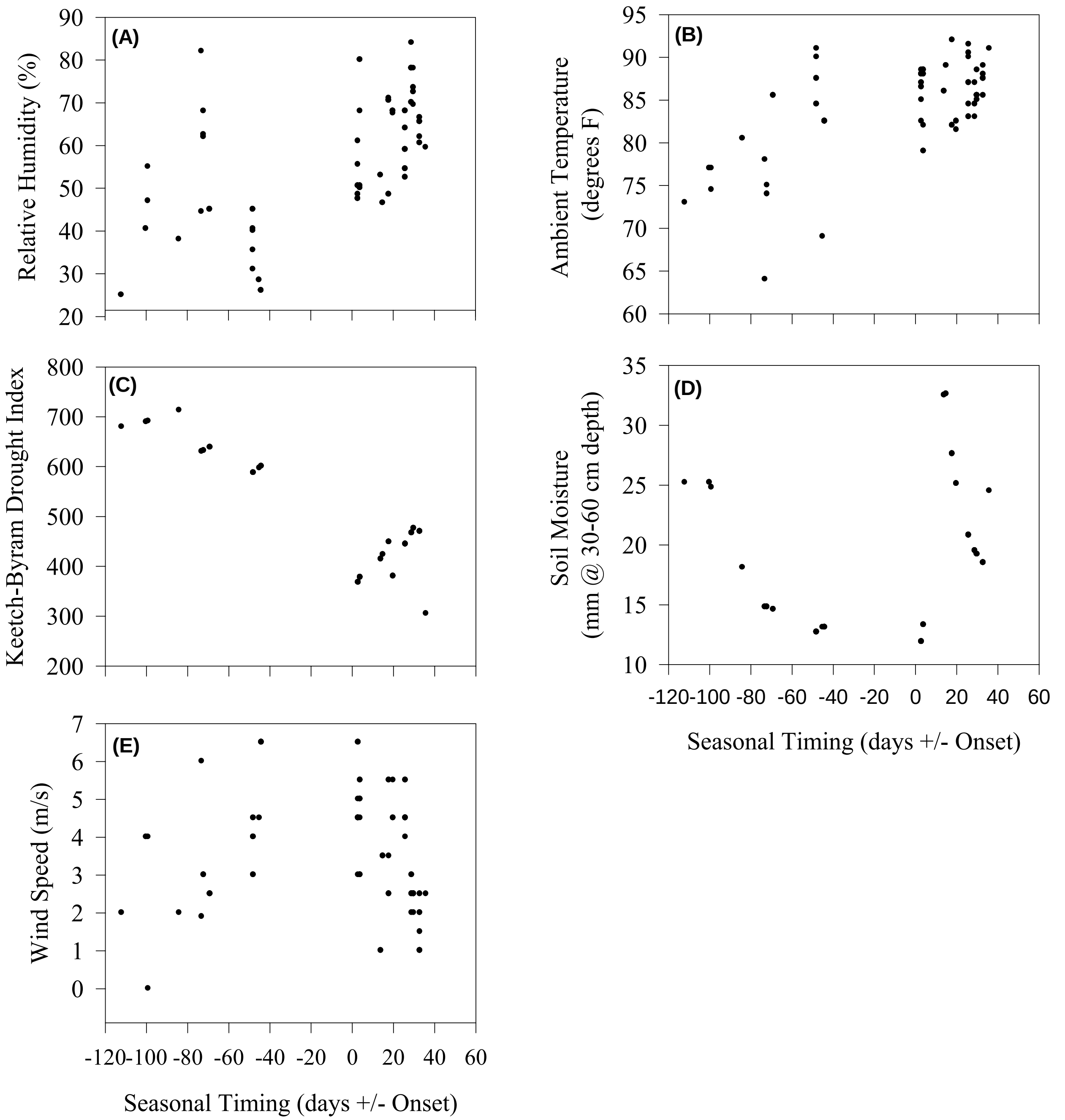

Figure 1. Relationship of seasonal timing (days +/- Onset) and weather variables during the 2007 fire season at Avon Park Air Force Range, south-central Florida, U.S.A. Seasonal timing is expressed as days before/after the Onset of the wet season, which was May 29, 2007 (denoted by zero). Onset was assigned using an analysis of annual cumulative rainfall anomalies for the 2007 fire season (Camberlin and Diop 2003). Weather variables include: (A) mean relative humidity, (B) mean ambient temperature, (C) Keetch-Byram Drought Index (KBDI), (D) soil moisture at 30-60 cm depth, and (E) mean wind speed.

the weather PC1 "seasonal weather" because the included weather variables were highly associated with seasonality (Figure 1B, 1C). PC2 of the weather PCA explained 26% of variance and included relative humidity, soil moisture, and wind speed. I grouped these variables under the title of "fire weather" because the relative humidity and wind speed typically varied greatly throughout the day and influenced fire on a much more local scale than the variables in PC1. By condensing weather into two PCs, I determined relationships among weather variables during fires and reduced the potential for multicollinearity.

Table 1. Rotated Principal Components Analysis – Relationships among variables describing fuel quantities and weather during prescribed fires in 2007 at the Avon Park Air Force Range, south-central Florida, U.S.A. Detailed are Pearson Correlations between principal components (PC) and (A) weather variables and (B) fuel quantity variables. Bolded factor loadings were used to define the factor and those in italics are considered to have some influence on the factor. Also included are eigenvalues and percent variance of the data set explained.

(A) Weather Variables	PC1: seasonal weather	PC2: fire weather	
Seasonal Timing	**0.90**	0.36	
Ambient temperature	**0.77**	-0.15	
KBDI	**-0.92**	-0.10	
RH	0.36	**0.77**	
Soil moisture	0.05	**0.70**	
Wind	0.13	**-0.82**	
Eigenvalues	2.71	1.58	
% Variance explained	45	26	
(B) Fuel Variables	**PC1: fine fuels**	**PC2: shrub**	**PC3: palmetto**
Dead fine	**0.86**	-0.04	-0.07
Live fine	**0.65**	-0.07	*-0.53*
Time since last fire	0.35	**0.71**	*0.47*
Shrub	*-0.44*	**0.63**	-0.05
Basal area	0.00	*-0.66*	0.27
Palmetto	-0.16	-0.12	**0.85**
Eigenvalues	1.77	1.35	1.04
% Variance explained	30	23	17

Relationships among fuel quantities

The PCA of pre-fire fuel quantity variables retained three PCs (Table 1B). Together, these PCs explained 70% of the total variation in the data set. PC1 of fuels (30% of variance explained) was named "fine fuels" because it had high correlations with dead and live fine fuel quantities. Also included in PC1 was a moderate negative relationship with shrub quantity and a moderate positive correlation with time since last fire. PC2 of the fuels PCA (23% of variance explained) was named "shrubs", due to a correlation with shrub quantity, but also represents a positive association with time since last fire and a negative relationship with pine basal area. PC3 (17% of variance explained), was named "palmettos" because palmetto quantity had the greatest correlation. Also, PC3 had a moderate positive association with time since last fire, and a moderately negative association with live fine fuels. Time since last fire has moderate to high correlation with all three fuel PCs, but is greatest in PC2. Thus, using a PCA, I was able to reduce the number of fuel quantity variables while still explaining a large amount of variation.

Effects of weather, fuels, and management on fire severity

Fuels and management had significant effects (p-value ≤ 0.05) on fire severity of the three fuel layers studied (groundcover, midstory, and canopy), but weather did not. The results of the multiple regression on fire severity of the canopy (i.e., char height, needle scorch, and needle consumption) resulted in a p-value for the model ≤ 0.0001 (Table 2) and was positively associated with head fires and the fuel principal component associated with palmettos (PC3) (Figure 2A). The multiple regression of the severity of the midstory had a p-value for the model of 0.0002 (Table 2) and was positively influenced by head fires, the PC associated with fine fuel quantities and the PC associated with shrub quantities (Figure 2B-D). The model chosen in the multiple regression for the fire severity of the groundcover resulted in a p-value of 0.01 (Table 2) and was positively influenced by the PC associated with shrubs. Thus, variation of fire severity within fuel layers existed within my study.

Table 2. Multiple Regressions – Stepwise selection for severity indices of fuel layers. Included are the combined adjusted R2 and F-values for the models, with parameter estimates and their F-values. Significance level to enter the model was α=0.15 and a significance level to stay at α=0.05. Statistics obtained from PROC REG.

Severity Index	Adj. R^2	Model F (p-value)	Parameter	Parameter Estimates	Partial R^2	Parameter F (p-value)
Canopy Fuel Layer	0.24	12 (<0.0001)	Intercept	-0.27		
			Head Fire	0.71	0.10	10 (0.021)
			Palmetto (PC3)	0.41	0.14	12(0.0007)
Midstory Fuel Layer	0.17	7 (0.0002)	Intercept	0.26		
			Head Fire	0.04	0.03	4(0.045)
			Fine Fuels (PC1)	0.03	0.11	13 (0.0005)
			Shrub (PC2)	0.02	0.03	4(0.043)
Groundcover Fuel Layer	0.06	7 (0.01)	Intercept	0.32		
			Shrub (PC2)	0.02	0.06	7 (0.01)

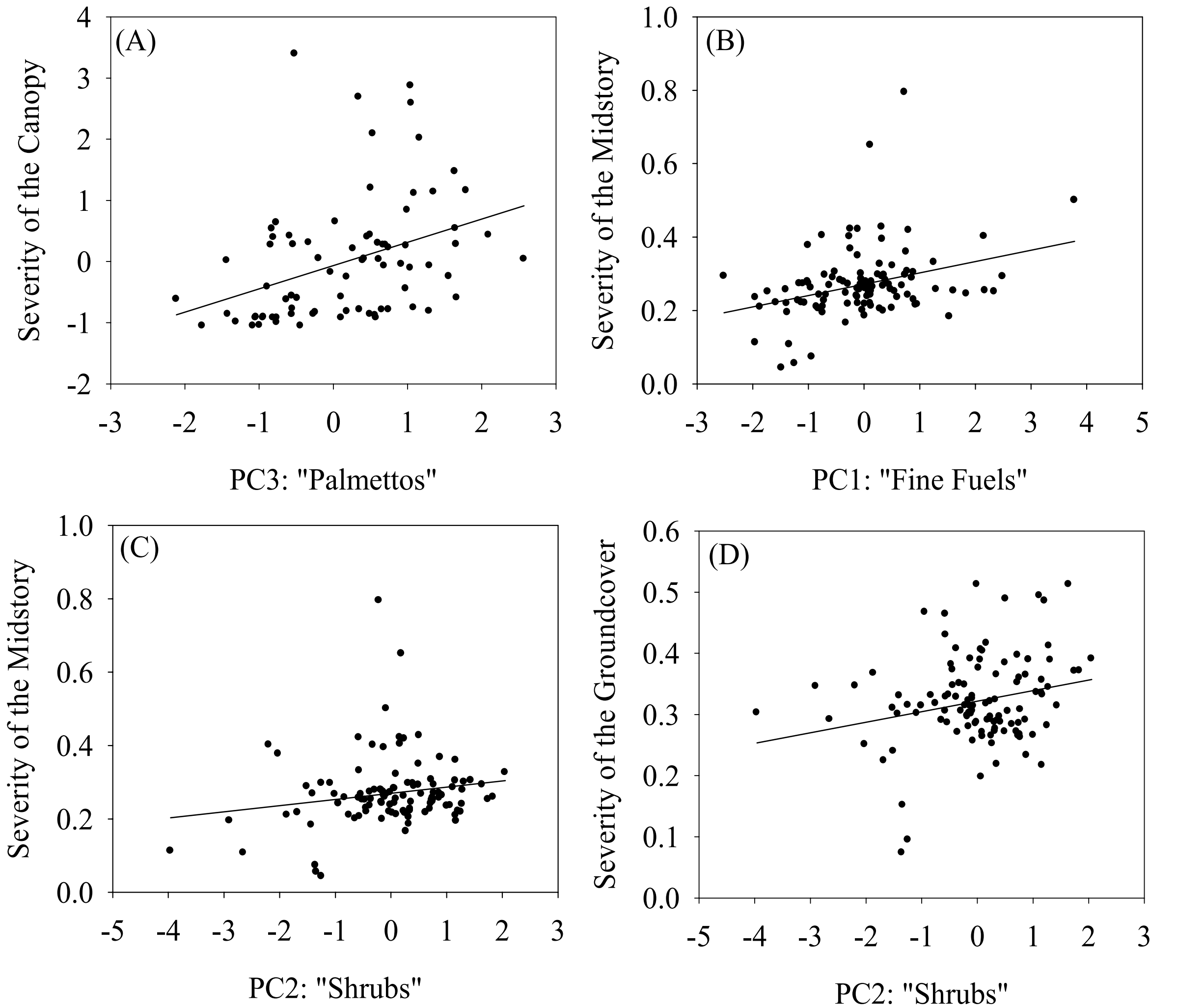

Figure 2. Relationships between indices describing fire severity of different fuel layers and principal components of fuels. Fire severity was determined for three different fuel layers: canopy, midstory, and groundcover. Indices of fire severity were based on the degree of fuel consumption of that layer and the quantity of fuels before the fire. Factor scores of fuel quantities included fine fuels (PC1), shrubs (PC2), and palmettos (PC3) as determined using a principal components analysis (table 1). The severity of the canopy was determined using a principal components analysis of char height in feet, needle scorch, and needle consumption. The severity indices of the midstory and groundcover fuels (Y axes) were calculated using Formula 1.0.

DISCUSSION

Variation in fuels

Local variation in fire severity in the prescribed fire regime at the Avon Park Air Force Range (APAFR) was associated with local heterogeneity in fuels. Heterogeneity of fuel quantities in this study varied temporally and spatially. As the time since last fire increased in pine flatwoods, the quantities of the fuel components (i.e., dead fine, live fine, shrub, and palmetto fuels) increased. This agrees with other studies that found the overall fuel load increases with time since last fire (Baeza et al. 2002; Sah et al. 2006). These fuel components are fire-adapted and recovery quickly after fires, especially when fires occur close to the onset of the wet season (Onset). Re-growth of the live fine fuels was observed in as little as two days after fires near Onset, as the vegetation sprouted from protected root systems. Similarly, palmettos leafed out rapidly from meristems, which protected live tissue from damaging effects of fires (Snyder 1986). Shrub quantities showed the highest association with time since last fire, indicating that shrub recovery may respond faster after a fire than other fuel components measured in this study. This may be due, however, to less intense fires occurring in shrub-dominated areas. Sah et al. (2006) suggested that less intense fires generally leave shrubs undamaged, allowing for their speedy recovery. The intensity of the prescribed fires in my study rarely resulted in the mortality of shrubs, allowing for rapid re-growth. Temporal heterogeneity of fuels (as associated with time since last fire) produced variation in the fire severity (as indicated by fuels scorch and consumption) of pine flatwoods, and this history of heterogeneous temporal variation produces spatial heterogeneity of the landscape.

Spatial heterogeneity among major fuel components and quantities in pine flatwoods existed in my study. Southeastern pine savannas have historically been maintained by natural, lightning-initiated fires, which result in small-scale heterogeneity of fire effects. This, in turn, has resulted in heterogeneity of fuels in the landscape. For example, Thaxton and Platt (2006) found that post-fire shrub environments in pine savannas ranged from areas with high shrub mortality due to high fire intensity, to areas where damage was minimal. Fuel components in my study showed positive and negative associations with each other. A moderate negative association of fine fuels with shrubs existed, possibly due to competition between the two components. Other studies have found that areas with high shrub abundance reduced the cover of wiregrass (Kirkman et al. 2001), due to shading and litter accumulation (Lemon 1949). Similarly, live fine fuel quantities had a moderate negative association with palmetto quantities, indicating a non-overlapping range of the two fuel components. Palmettos contain large fan-shaped fronds, shading the groundcover beneath them and inhibiting fine fuels from establishing. Disconnection among midstory fuels and pine trees was also found. Pine trees compete with fuel types in the mid- and under-story via root systems (Kirkman and Mitchell 2006). Thus, spatial heterogeneity fuels existed in my study, which resulted in heterogeneity of fire severity.

Effects of fuels and management on fire severity

Temporal and spatial heterogeneity in fuels resulted in variation of fire severity. I analyzed fire severity by documenting fuel scorch and consumption of three fuel layers: the groundcover, midstory, and canopy. The severity of the groundcover fuel layer consisted of scorch and consumption of the fine fuels, while the severity of the midstory fuel layer contained scorch and consumption of shrubs and palmettos. The fire severity of the canopy, on the other hand, included the char height (scorch of flames on pine trunk), needle scorch, and needle consumption in the pine canopies. The fire severity of each fuel layer was influenced by different fuel quantities and ignition techniques (management practices). The variation in fuels prior to the fires and the different ignition techniques used, therefore, resulted in variation of fire severity in among the different fuel layers.

The fire severity of the groundcover fuel layer was affected only by PC2 of the fuel PCA (Table 1). Within PC2, a positive correlation with shrubs and time since last fire exists, while a negative association with pine basal area exists. I postulate that the time since last fire most strongly influenced the severity of the groundcover fuels in this study for three reasons: 1) pre-fire fine fuels and time since last fire had moderate positive associations in PC1; 2) pre-fire fine fuel and shrub quantities showed a moderate negative association in PC1 of the fuel PCA; and 2) pines should contribute to the fuel load of the dead fine fuels in the groundcover, fueling the fires occurring in this layer. Additionally, the negative association between shrubs and pine basal area in PC2 coupled with the negative association of shrubs and fine fuels in PC1 may be cancelling out the pine needle contribution to the fine fuel layer. Thus, fine fuels increased with time since last fire, contributing to the fuel load of the groundcover fuels, and allowing more fuels available for burning.

The severity of the midstory fuel layer was influenced by head fires along with PC1 and PC2 of the fuel PCA. Head fires typically have greater flame lengths, allowing flames to reach the midstory fuel layer and influence fire severity. Similarly, within many pine flatwoods in my study, fine fuels (PC1) served as a vertical fuel layer for flames to travel upward into the midstory fuels (i.e. shrubs and palmettos). Although fine fuels did not typically establish underneath palmettos, they existed side-by-side within the landscape. Within PC2, greater shrub quantities contributed to the severity of the midstory because of the contribution of shrubs to the midstory layer. With a greater number of shrubs, the shrubs and palmettos of the midstory burned at a greater severity. Additionally, as time since last fire increased, palmetto quantities increased in pine flatwoods of my study, increasing the severity of the midstory. Lastly, a negative association of pine basal area with the fire severity of the midstory, along with the negative association between shrubs and pines in PC2 suggests that the competition between the midstory fuels (i.e. shrubs and palmettos) and pines reduced the overall fuel load of the midstory, and thus reduced the severity.

In the canopy fuel layer, severity of burn (as indicated by consumption of pine needles and char height) increased with greater amounts of palmettos and with head fires. For fires to influence pine canopies, flames must be able to generate enough heat to scorch pine needles. Head fires typically have greater flame lengths than either flanking or backing fires, such that more heat rises into the canopy, resulting in more intense fires (Van Wagner 1973; Ryan 2002; Dickinson and Johnson 2001). Palmettos at the APAFR ranged from one to one and one-half meters in height, creating a vertical fuel ladder that allowed a great amount of heat to reach the canopy, resulting in scorched or consumed needles. Fire severity of pine canopies was associated with palmetto quantities and head fires.

Effects of weather on fire severity

Weather variables were not found to have significant effects on fire severity of any fuel layer. Seasonal variation in weather existed (Figure 1), yet the effects were not significant. Thus, it would seem that this variation in weather would produce variation in fire severity. Many studies have found that weather conditions (e.g., relative humidity, wind speed, temperature, and drought) influence fire severity and intensity in southeastern pine savannas (Baeza et al. 2002; Thaxton and Platt 2006). Beckage et al. (2005) even suggests that climate can be used to determine when natural fires typically occur, including their variation and responses of the environment. Additionally, variation among years due to the El Niño-Southern Oscillation (ENSO) resulted in differences in fire severity as indicated by number of wildfires or area burned (Beckage et al. 2003, 2005; Slocum et al. 2003, unpublished data). The findings of my study, however, contrast strongly with other studies of fire severity or intensity in pine savannas.

I postulate that weather was not found to be significant due to management practices (e.g., ignition techniques, firebreaks, spot ignitions) as well as fire history. Fire managers at the APAFR make decisions regarding which area to burn, and on which day, depending on the weather, time since last fire, existing fuel components, habitat type, and amount of resources available (e.g., personnel, trucks, equipment). For example, landscapes that have the potential for producing severe effects or spotting may be burned when more firefighters are available. With greater resources, head fires are ideal for burning large areas safely in a short amount of time. Similarly, managers can use spot ignitions, which are set by hand, flare, or helicopter, in which the resultant fires draw wind from each other, reducing the overall intensity of the fire and allowing managers more control. Fire managers also control fires by altering their tactics once the fire has been started. By utilizing techniques such as spot ignitions, fire strips, and backing lines during the fire, managers minimize the potential effects of weather by controlling the fire's behavior.

The frequency of fire at the APAFR may have also reduced the effects of weather on fire severity. Unlike other areas in central Florida, much of the APAFR landscape is in good to excellent natural condition due to a long, uninterrupted fire regime (Orzell 1995) with no periods of effective fire suppression. Fires, including wildfires, ordnance fires (resulting from bombs), and prescribed fires, have maintained the ecological integrity of landscapes within the site since its establishment during World War II. In 1943 and 1944, APAFR was the world's largest bombing range (The Nature Conservancy 1994), which resulted in ordnance fires year-round, sometimes during times of drought when other parts of Florida where fire suppressed. Prescription fires at my study site have been used as the primary management tool since the early 1970s. Prior to 1977, head fires were set in pine flatwoods during the dormant season (December to March) on a two-year rotation (Van Hook 1995). In 1977, backing fires set during the dormant season became the practice for all controlled burning, but resulted in shrub encroachment and was therefore reevaluated in 1990 (Van Hook 1995). Since then, more ecologically sound growing season fires have been used on a 2-3 year rotation to manage pine flatwoods, including composites of head, backing, and flanking fires (Van Hook 1995). This long and interrupted fire regime of the APAFR allows managers to have more control over the fires, working to ensure that the entire landscape burns completely. This completeness of fires, however, may not allow for the small-scale heterogeneity that results from natural fires.

Moreover, other objectives from outside agencies often dictate when and where fire managers can burn. Most notably is the suppression of fires during times of drought, when lightning fires and other wildfires are most likely to occur (Beckage et al. 2003; Slocum et al. 2003). During my study, a statewide burn ban was imposed for nearly 40 days while areas in Florida's panhandle and coasts were experiencing severe drought and several large wildfires. During this time, however, my study site received ample rainfall and was under ideal conditions for controlled fires. Other objectives, including those from the Endangered Species Act, other land users (e.g. foresters, ranchers), and recreation activities (e.g. camping, hunting) at the APAFR must be considered in the prescribed fire regime. The many objectives involved in implementing prescription fires, however, often result in fires that produce fire effects that are not suited for maintaining the habitat or ecosystem integrity in pine flatwoods.

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VITA

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